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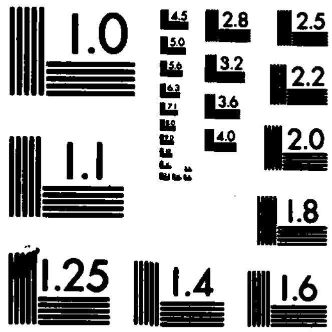

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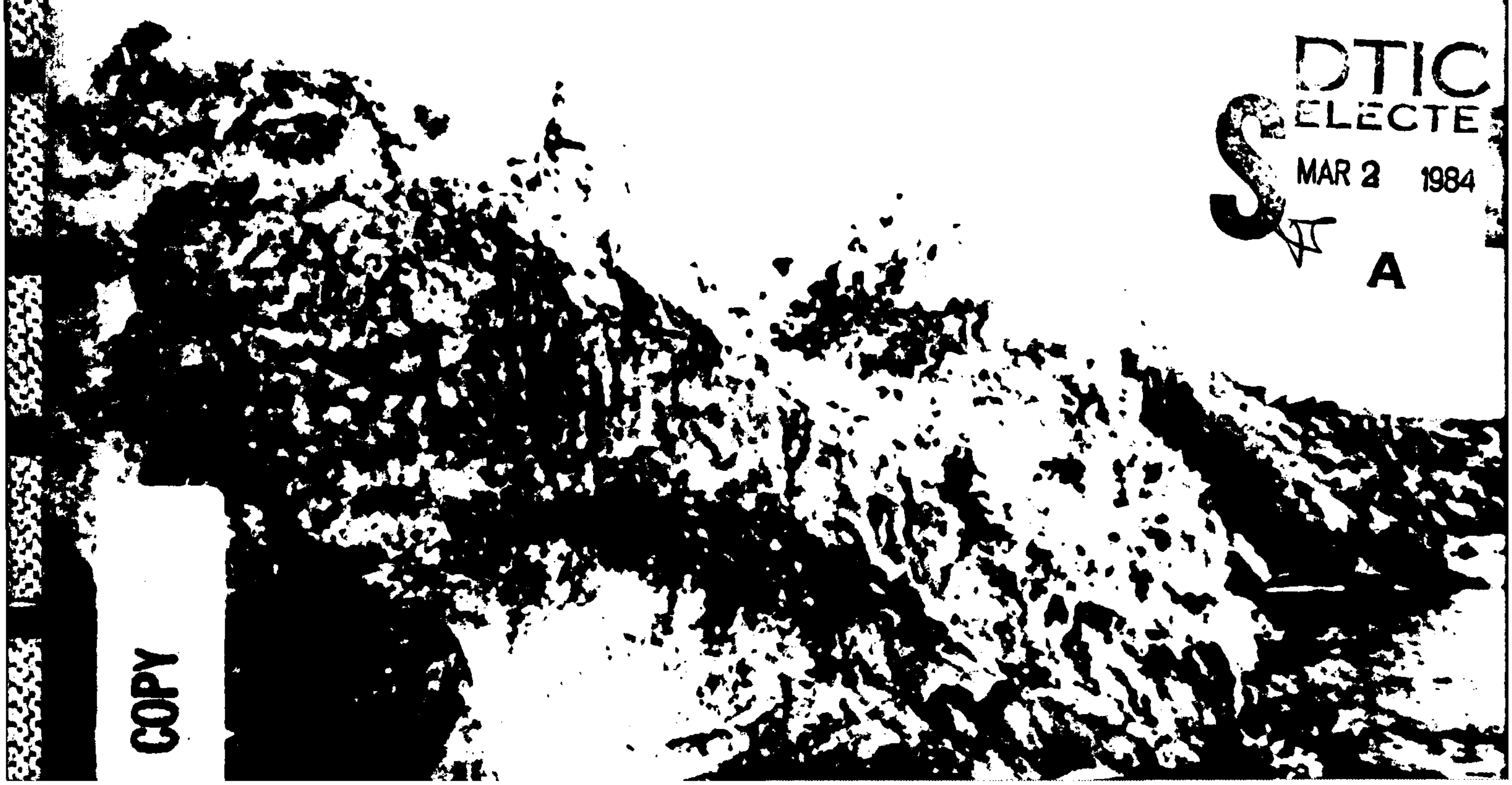
Erosion of perennially frozen streambanks



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Cover: Actively eroding bluff of perennially frozen, ice-rich silt in northern Alaska (photo, James Ebersole).

CRREL Report 83-29

December 1983

Erosion of perennially frozen streambanks

Daniel E. Lawson

Prepared for
U.S. ARMY ENGINEER DISTRICT, ALASKA

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A literature review indicated that the effects of permafrost on streambank erodibility and stability are not yet understood because systematic and quantitative measurements are seriously lacking. Consequently, general controversy exists as to whether perennially frozen ground inhibits lateral erosion and bankline recession, or whether it increases bank recession rates. Perennially frozen streambanks erode because of modification of the bank's thermal regime by exposure to air and water, and because of various erosional processes. Factors that determine rates and locations of erosion include physical, thermal and structural properties of bank sediments, stream hydraulics and climate. Thermal and physical modification of streambanks may also induce accelerated erosion within permafrost terrain removed from the immediate river environment. Bankline or bluffline recession rates are highly variable, ranging from less than 1 m/year to

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over 30 m/year and, exceptionally, to over 60 m/year. Long-term observations of the physical and thermal erosion processes and systematic ground surveys and measurements of bankline-bluffline recession rates are needed.

PREFACE

This report was prepared by Dr. Daniel E. Lawson, Research Physical Scientist, of the Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was funded by the U.S. Army Engineer District, Alaska, under Intra-Army Order E86-83-006, *Conduct Studies on the Tanana River During Fiscal Year 1983* and by the Office of the Chief of Engineers under Civil Works Work Unit CWIS 31568, *Erosion Potential of Inland Shorelines and Embankments in Regions Subjected to Freezing and Thawing;* Research Area, *Environmental Quality*; Research Program, *Environmental Impact*, and Civil Works Work Unit CWIS 31722, *Sediment Transport and Deposition in Northern Rivers*; Research Area, *Flood Control and Navigation*; Research Program, *Hydrology of Cold Regions.*

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Daniel E. Lawson

INTRODUCTION

This report presents the results of an in-depth review of literature on the effects of erosion on perennially frozen streambanks and recommends future research needs based upon that review. Frozen banks in northern rivers may be an extremely important factor determining the location and rate of bankline recession. It is therefore critical to evaluate the current state of knowledge in order to select appropriate bank stabilization techniques for minimizing bankline recession.

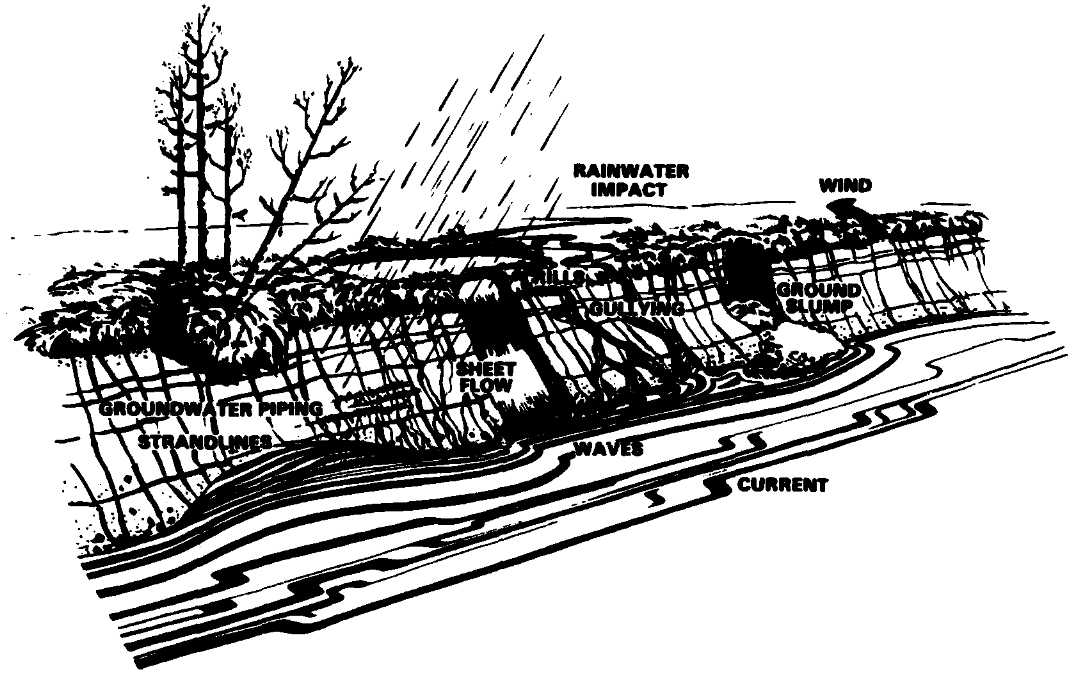
In order to address this subject, several questions need be asked. First, what effect does permafrost have on a river's typical erosional processes? Second, does permafrost result in additional erosional processes that are *unique* to perennially frozen banks? Third, what factors modify or affect the thermal condition of a bank and how will they affect erodibility? Fourth, how do rates of erosion and recession of permafrost banks compare to those in similar unfrozen banks?

I found that none of these questions had been adequately addressed by previous studies; however, I will discuss the current understanding of their answers, and, because of the very limited number of studies that have approached these questions directly, I will also refer to other applicable studies.

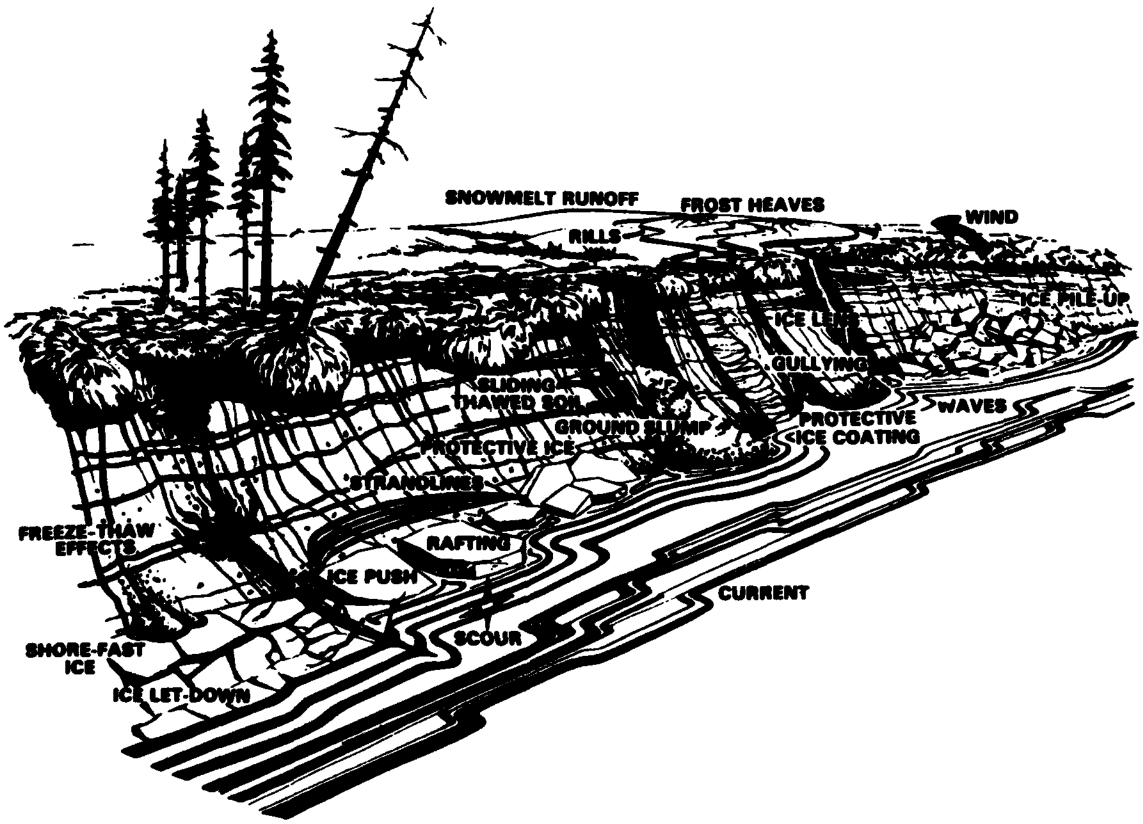
STREAMBANK EROSIONAL PROCESSES

Streambanks in all rivers are attacked by erosional processes (Fig. 1). These processes cause deterioration (such as weathering) or entrainment of materials composing a bank (Table A1), reduce stability and cause bank materials to fail (Table A2), or physically transport sediment from the eroding bank (Table A3). They include subaerial processes acting on exposed upper streambank sediments and subaqueous processes acting on submerged streambank and channel bed materials.

In general, bank failure and particle-by-particle losses are not caused by a single process, but rather by a combination of processes that interact with bank materials of differing properties (Fisk 1952, Wolman 1959, Turnbull et al. 1966, Brunsden and Kesel 1973, Thorne 1978, 1982, Hooke 1979, Thorne and Tovey 1981, Whitten and Patrick 1981, Lawson, in prep.). The dominant process that determines the rate of erosion and bankline recession may vary from site to site along a river, in accordance with the size, geometry and structure of the bank, the engineering properties of the bank material, the hydraulics of flow in the channel and climatic conditions (e.g., Thorne 1978, 1982). Erosion at a specific site is also clearly affected by hydrologic events elsewhere within the drainage basin (Schumm 1960, 1963, 1971).



a. Unfrozen conditions.



b. S ʼasonally frozen conditions.

Figure 1. Idealiz. ʼ-ʼvin , the erosional processes commonly attacking streambanks.

Cohesionless, cohesive or, more importantly, composite stratified bank materials react differently to erosional forces. Cohesionless particles are readily loosened and entrained by fluvial processes (e.g., Carson 1971, Thorne 1978). Cohesive material resists erosion by fluvial entrainment unless it is loosened or weakened by other bank processes, such as freezing and thawing, ice action, increased pore water pressure and animal activity (Wolman 1959, Hooke 1979, Thorne and Lewin 1979). Failure of cohesive sediments by gravitational force is perhaps more important and certainly more common in composite banks of interbedded cohesive and cohesionless sediments (Krinitzsky 1965, Brunsden and Kesel 1973, Thorne and Tovey 1981, Grissinger 1982).

Research on streambank erosion and associated fluvial processes under unfrozen conditions is abundant, and a more thorough analysis of it is beyond the scope of this review. The reader is referred to the classic paper of Sündborg (1956) and texts by Leopold et al. (1964), Graf (1971), Shen (1971), Yalin (1977), Gregory (1973), and Garde and Raju (1977) for detailed discussions of hydraulic processes and fluvial geomorphology in relation to erosion and deposition in river systems. Recently, Keown et al. (1977) and Dardeau (1981) presented literature surveys on streambank erosion and protection under unfrozen conditions. The Corps of Engineer's final report to Congress on the Streambank Erosion Control and Demonstration Act of 1974 (U.S. Army Corps of Engineers 1981) also summarizes recent studies of erosion (in particular, Appendix C of the report) and streambank stabilization techniques for unfrozen banks.

PERMAFROST AND RELATED FACTORS

Permafrost, or perennially frozen ground, is any material in which a temperature below 0°C has existed continuously for at least 2 years (Muller 1947). Perennially frozen ground is thus defined only on the basis of temperature, and specific material properties (such as lithology or water content) are not implied. The erosion of perennially frozen ground clearly will involve the modification of two distinct states that may affect the sediment's erodibility—the physical and the thermal.

The distribution of permafrost is controlled principally by climate, but factors such as topography, vegetation and surficial features that act as heat sinks (e.g., lakes or rivers) may determine its local distribution (e.g., Ferrians et al. 1969, Brown and Péwé 1973). In Alaska, for example, the distribution of permafrost is continuous mainly north of the Brooks Range and becomes discontinuous farther south (Ferrians 1965, Washburn 1980, p. 28). Local factors become increasingly more important in determining where permafrost occurs in the more southerly regions.

Although the definition of permafrost considers only temperature, certain properties develop that are unique to perennially frozen ground that will affect its response to erosional forces. Of particular importance is the content, type and distribution of ice within it. The geotechnical properties of sediment while frozen and while thawing are affected by the presence of ground ice, especially bearing capacity, slope stability and settlement (Andersland and Anderson 1978, Johnston 1981). Similarly, the response of permafrost terrain to natural or human disturbances is clearly affected by ice content (e.g., Mackay 1970, French 1974, 1975, Lawson and Brown 1979, Lawson 1982). Substantial quantities of ice (60 to 90% by volume) have been observed in sediments at depths up to 45 m (e.g., Black 1969, Rampton and Mackay 1971, Mackay 1971, 1973, Mackay and Black 1973, Brown and Sellmann 1973, Williams and Yeend 1979, Pollard and French 1980, Lawson 1983). The content and distribution of this ice is a function of several factors, only a few of which, unfortunately, have been studied sufficiently (Mackay and Black 1973, Mackay et al. 1978). Although researchers have generally recognized that there are large volumes of ice in fine-grained sediments, significant exceptions to this generalization exist that are apparently related to geologic factors not accounted for by this simple grain-size relationship (Lawson 1983). In fact, our limited understanding of ground ice occurrence makes it currently impossible to predict its presence. Detailed subsurface investigations are thus needed to determine the effect of ground ice on the erodibility of streambanks at a particular location.

Observations of the response of permafrost terrain to disturbance illustrate the importance of ground ice to streambank erodibility. When the thermal regime of ice-rich permafrost terrain is disturbed, it may undergo rapid and widespread thaw subsidence (Muller 1947, Terzaghi 1952). Excess pore pressures develop within the thawing, ice-rich sediment that reduce its effective stress and may result in failure of the thawing slope (Morgenstern and Nixon 1971, McRoberts and Morgenstern 1974a). Melting of massive ice can similarly cause failure in overlying sediments, usually because of excess pore pressures that can build up rapidly over a short period (Nixon 1973). The thawed sediment can fail on very low angle slopes of 5° to 15°, far below the natural angle of repose of the material when dry and unfrozen. As a consequence, other degrading processes may start—for example, the slump or flow of materials in slope or the gullying and removal of thawed sediment by meltwater in areas with sufficient relief (Mackay 1966, 1970, Ferrians et al. 1969, French and Egginton 1973, French 1974, 1975, McRoberts and Morgenstern 1974a, b, Lawson and Brown 1979, Lawson 1982). The lateral migration of a river channel is one possible natural process that can begin thermal degradation of the perennially frozen sediments exposed in its banks.

After thawing, formerly ice-rich sediments with visible excess ice are generally oversaturated (Mackay 1966). Such high water contents will also reduce shear strengths (Nixon and Hanna 1979). This increases the material's susceptibility to failure by shear and thus reduces the resistance of thawing sediment in banks to current-generated shear at the water/sediment interface. In all instances, if water can drain away or dissipate sufficiently to minimize the loss of shear strength, critical failure conditions may not be attained.

PERMAFROST AND EROSION

General

In a general sense, permafrost has two effects on streambank erosion: directly, as a component of banks that are under attack by erosional forces and indirectly, as a factor affecting watershed hydrology. Although unsaturated, seasonally frozen sediments may permit infiltration of surface water (Slaughter and Kane 1979, Kane 1980), the more prevalent saturated, perennially frozen ground is generally impermeable and restricts recharge, discharge and movement of groundwater, acts as a confining layer, and limits groundwater storage capacity (Williams 1970). Effects on the watershed may, for example, be to increase the proportion of surface water flow to total runoff (McDonald and Lewis 1973) as well as its rate of flow into streams and thus to increase the hydrographic rise and period of peak flow (Dingman 1975). In continuous permafrost areas, groundwater flow may be restricted to alluvium beneath active channels (e.g., Williams 1970, Dingman 1975).

The relationship of streambank erosion to permafrost distribution within a drainage basin is not known. Scott (1978) has suggested that the hydrologic and climatic character of permafrost regions may influence streambank erosion more than the presence of perennially frozen ground in banks. His limited data suggest that drainage area, bed composition, channel pattern and climate (and thus the occurrence of breakup) are related to the timing and rate of bank erosion. Similar relationships of bank erosion to discharge, climate and channel activity were suggested by Walker (1969, 1978), Outhet (1974a), Ritchie and Walker (1974) and others. Church (1972) and McDonald and Lewis (1973) also suggested that increased discharge in gravel-bed rivers results in increased velocity and lateral channel widening, but little increase in depth. They thus suggest that within permafrost regions, lateral bank cutting is more important than scour in channels in compensating for increased discharge.

Erosional processes

The erosion of streambanks will be discussed in terms of two components—an upper section of streambank exposed to the air (subaerial) and a lower submerged section (subaqueous). Because water level often changes, however, a transitional zone affected by subaqueous and subaerial processes lies between them. Although erosional processes differ in each zone, most observations within the literature to date have been only of subaerial processes. Process interaction and response in the transitional zone are virtually unstudied.

In this report, the upper exposed section is termed the *bluff zone* and the submerged section, the *bank zone* (Fig. 2). Also, bank or bluff *erosion* refers only to a *net removal of material. Bankline recession* is the lateral, landward translation of the water line. Some contradictory discussions in the literature result from a lack of distinction between these two concepts.

Thermal and mechanical processes appear equally important in causing bankline recession in northern rivers. These processes are interrelated, a fact emphasized in Are's (1973, 1977) grouping of erosional processes acting on frozen banks in reservoirs. They are 1) thermoabrasion—erosion of bank materials attributable to the thermal and mechanical energy of moving water, 2) thermokarst—subsidence resulting from thaw of frozen bed and bank materials, and 3) thermodenudation—subaerial processes acting on bluff materials

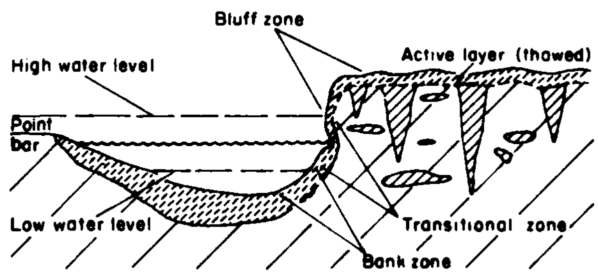


Figure 2. Distinction between bank and bluff zones of eroding, perennially frozen streambanks. Transitional zone is affected by subaerial and subaqueous processes common to both the bank and bluff zones because of water level fluctuations. Closely spaced cross hatching denotes ground ice; wider spaced hatching denotes frozen sediments.

thawed by increasing air temperatures and solar radiation. Each mechanism of bank or bluff erosion identified in the literature and discussed below falls into these groups.

Bank zone processes

Bank material, as well as material of the riverbed, is mechanically eroded mainly by currents and by wind-generated waves. While a number of authors have commented on the importance of wind waves in causing bank erosion at the base of bluffs (Williams 1952; Lewellen 1965, 1972; Walker and Arnborg 1966; Outhet 1974a, b; Miles 1977; Hollingshead and Rundquist 1977), few have observed the variability in erosion by currents and waves and the resulting bank form along a particular reach. Similarly, variability in erosion process and bank form between braided and meandering reaches and other local changes in channel pattern because of frozen ground have been suggested by Scott's (1978) data, but these also have not been analyzed. Further, only Scott (1978) has measured scour rates of bed and bank material in arctic streams. Scott concluded that frozen conditions retarded the rate of scour by currents during and after breakup, so that scour only took place in larger channels after channel bed and bank materials thawed. Smaller channels showed little change over the period of study and Scott (1978) suggested that frozen ground had prevented scour.

Miles (1977) considered currents and waves also particularly important in removing sediments that are sloughed from bluff faces onto the banks and thus in maintaining a steep bank and bluff profile. Locations where currents continually impinge upon sloughed materials and can entrain them will erode more rapidly during high-water periods than will locations where currents are absent, apparently because scour maintains a direct contact between the water and frozen sediment, thereby inducing thaw (Shah 1978). At locations where the products of mass wastage are not removed, bluff and bank slopes become relatively stable over at least the short-term because of the insulating effect of the thawed sediment cover. Bluff slope angles are gradually reduced as more and more of the slope becomes covered by thawed sediment.

The temperature of water in streams in northern permafrost regions is often within 1° to 3°C of freezing throughout most of the flow season. Because the ability of currents to entrain and transport sediment is affected by water temperature, this effect needs to be considered in evaluating the effects of permafrost from both a physical and thermal point of view. Studies of unfrozen beds and banks indicate that decreasing water temperatures increase the rate and effective particle size of suspended sediment in transport, if other factors such as discharge and bed material properties remain constant (e.g., Straub et al. 1958; Ali 1961; Colby and Scott 1965; Toffaleti 1968; Taylor and Vanoni 1972a, b; Shen et al. 1978). An increase in suspended sediment transport results because the viscosity of water increases as the water temperature decreases. Viscosity is about twice as large at 0°C as at 25°C and, thus, the fall velocity of particles suspended in water is much less.

The effect of water temperature on bedload transport is not as well defined, but it may be similar (e.g., Colby and Scott 1965; Taylor and Vanoni 1972a, b; Shen et al. 1978). If so, the low water temperatures common to northern rivers in permafrost regions, particularly during breakup, should be conducive to increased erosion by currents and breaking waves. Unfortunately, temperature effects on scour of frozen or thawing banks have not been investigated.

When waves attack frozen banks, they erode a niche into it at the water's edge (Fig. 3). Waves are thus important components affecting transitional zone sediments. The eroded niche is usually called a thermo-

Figure 3. Cantilevered blocks of frozen sediment above thermoerosional niche, northern Alaska.

erosional niche because of its formation by both thermal erosion and mechanical processes (Abramov 1957). Such niches can become rather large and extend deeply into bank and bluff sediments before the overlying materials fail (e.g., an 8- to 10-m depth was reported by Walker and Arnborg [1966]).

The critical depth of the niche at failure is a function of bluff height and frozen-ground material properties, including planes of weakness along ice wedges and other massive ice bodies (e.g., Harper 1978). In banks of uniform composition, niching apparently is deepest in fine-grained silt and clay (5 to 10 m) and less in sand and coarser-grained sediment (1 to 3 m) (Miles 1977). This failed material will protect the bank from further niche development until currents and waves erode it away (Dylik 1969). Numerous authors have discussed the occurrence and apparent importance of thermoerosional niches in causing recession of perennially frozen banks (Leffingwell 1919; Williams 1952; Waller 1957; Walker and Morgan 1964; Czudek and Demek 1970; Gill 1972; Outhet 1974a, b; Lewellen 1972; Ritchie and Walker 1974; Miles 1977; Hollingshead and Rundquist 1977; Walker 1978).

The initial development of niches is determined mainly by the wave energy impinging upon the bank, water temperatures and bank composition (Williams 1952, Lewellen 1965, Walker and Arnborg 1966, Ritchie and Walker 1974). Wave energy is related to wave height and will depend upon wind velocity, effective fetch (length and width of water surface over which the wind blows), wind-storm duration and water depth (Komar 1976, Bhowmik 1978). Studies of wind waves on coasts also suggest that the interaction or interference with currents may increase or diminish the effective wave height and intensity at the shore face (Komar 1976). Thus, within a river, wave attack will vary with the orientation of the channel axis and its width in relation to the prevailing wind direction (Williams 1952; Outhet 1974a, b). Outhet (1974b) also reported that waves can develop beaches at the base of bluffs. Such newly developed beaches are then affected by subaerial and subaqueous erosion.

Niche development also depends upon fluctuations in water level. A niche of a height greater than the predominant height of waves striking bank sediments may result from fluctuating river stages, with the extent and shape of the niche depending on the length of time the water remains at a particular location on the bank face (Walker and Arnborg 1966; Lewellen 1965, 1972). The general effect of rising (or falling) river stage is to move the location, duration and, possibly, intensity of wave and current attack on bank and transitional zone sediments. In addition, thermal effects will translate up or down the frozen sediments with the rise or fall of the relatively warmer water.

According to Ritchie and Walker (1974), heat exchange processes are much more effective between water and sediment than between air and sediment, and thus submerged sediments should thaw more rapidly than subaerially exposed materials.

The growth of thermoerosional niches is sometimes cited as being most significant during high-water stages in spring breakup (e.g., Walker and Arnborg 1966, Scott 1978). Other authors have suggested that high water during summer floods is more important than at spring breakup because channel beds, banks and bluffs remain frozen during most of breakup (e.g., Abramov 1957, Miles 1976). Even with a lowering of the water surface, however, warm air can continue the thawing of sediments exposed in niches. Observations to date suggest that the thermal effects of warmer air and warmer water during the summer and the variability in the thermal properties of sediments commonly present in banks may be as important as the timing of hydrologic events in causing niche growth and thus bank and bluff erosion.

Physical characteristics of bank sediments that determine their thermal properties (e.g., Nixon and McRoberts 1973), particularly grain size and ice content, are cited as important parameters (although in conflicting ways) in determining the rate of niching and the development of bank form (e.g., Cooper and Hollingshead 1973, McDonald and Lewis 1973, Outhet 1974a, Ritchie and Walker 1974, Miles 1977). Scott (1978), for example, found that niching was faster in coarse-grained sediment because of its greater rate of thaw and subsequent erosion. Cohesive sediments exhibited slower thaw rates and, once thawed, provided more resistance to erosion than the coarser, cohesionless materials. In contrast, Miles (1977) concluded that since ice contents are largest in finer-grained materials, this effect results in finer-grained sediments actually being more erodible than coarser, cohesionless and usually ice-poor sediments.

According to Are et al. (1979), ice content exerts a strong control on shoreline retreat in reservoirs and lakes. Pure ice shores would retreat indefinitely under the simple presence of water above 0°C. If the shores contain no ice, however, thermal energy from the water would have no direct influence on reshaping the shoreline. This effect is evident in banks composed of extremely ice-rich sediment or containing large, tabular ice bodies and ice wedges. Ice wedges, for example, melt quicker than adjacent thawing sediments that contain much less ice, resulting in a digitating bankline with gullies located where wedge ice had melted (Ritchie and Walker 1974). Mackay (1963) observed rapid retreat rates where tabular (2 to 5 m thick) ice bodies were exposed by niching in coastal bluffs of northern Canada.

Melting of ice can also cause a collapse and settlement of channel bed and bank materials. This results in remolding and restructuring of the thawed sediment that may simultaneously reduce its resistance to shearing and increase its erodibility. In addition, the moisture content of sediment after it is thawed can remain high because of the impermeable nature of the underlying still-frozen ground; thawing, therefore, can limit the shearing resistance of the material because it is undrained and can further facilitate mechanical erosion. Shamanova (1971) has suggested that the instability of ice-rich frozen ground upon thawing caused accelerated rates of erosion and bankline recession in permafrost regions.

Bluff zone processes

Bluff sediments may be reworked or eroded by a variety of processes, including some unique to frozen ground. An unstable condition clearly may result from thermoerosional niching beneath the bluff. Undercutting of bluffs by niching, as well as by the direct impingement of river currents, subsequently results in a block collapse (also termed block slumping, block sliding, fall landsliding and spalling), a process quite often cited as the most important mode of failure of perennially frozen bluffs along rivers and coasts (Leffingwell 1919; Williams 1952; MacCarthy 1953; Waller 1957; Walker 1969; Gill 1972; Outhet 1974a, b; Miles 1977; Are 1977; Hartz 1978; Scott 1978).

In this process, thermal niching causes a frozen block of sediment to be cantilevered out over the water surface (Fig. 3). Such blocks range up to 10 m or more across. These blocks rotate out and forward and fall after a tensional failure along a plane located above the head of the niche. Preferential failure planes may also develop along planes of weakness within thawing or actively cracking ice wedges, or on melting surfaces of segregated ice bodies (MacCarthy 1953, Walker and Arnborg 1966, Walker and McCloy 1969).

A frozen peat layer will remain stable longer than mineral matter because of its insulating qualities. Thus, exposed ice wedges within it melt much more rapidly by comparison. Since large peat blocks generally overhang thin erosional niches, collapse drops the block only a short distance and rotation is slight (Walker 1969). These blocks then provide some buffering of banks and bluffs from attack by waves and currents. In addition to the insulating effect of continuous vegetation mats, intertwined roots also provide additional strength to resist block failure and collapse (Smith 1976).

Additional slope failure mechanisms recognized along coastal or river bluffs fall in three classes–slip, flow or a combination of the two, such as slip leading to flow (Fig. 4). The distinction among these mechanisms is that in slip, discrete blocks of thawed or frozen sediment slide or slump along an often arcuate failure plane that either intersects the surface between frozen and thawed sediment, or lies within a thawed zone beneath otherwise frozen ground (Mackay 1966; McRoberts and Morgenstern 1973, 1974a, b; McDonald and Lewis 1973; Lewis and Forbes 1974; Outhet 1974a; Miles 1977; Harper 1978; Church and Miles 1982). The latter case is apparently more common in areas of thin or discontinuous permafrost.

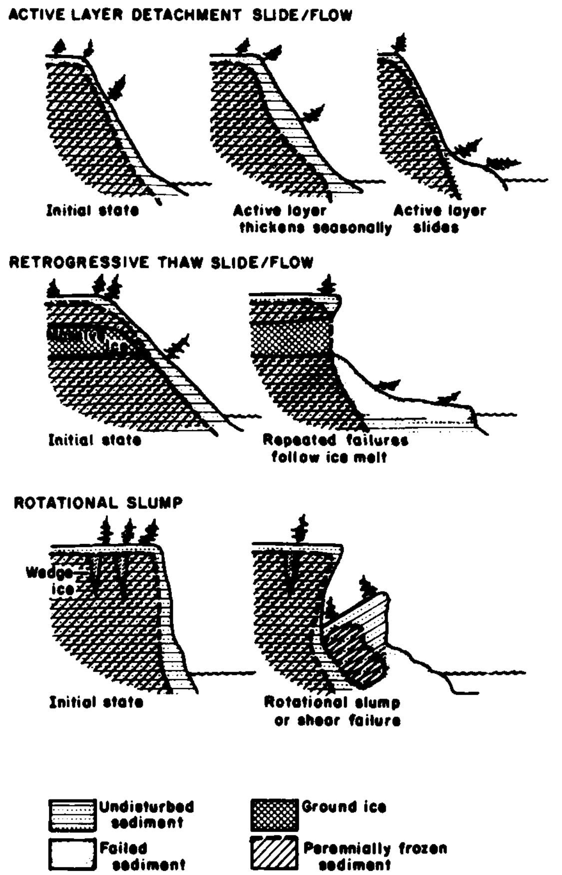


Figure 4. Examples of bluff zone failure mechanisms associated with ground ice presence (after Church and Miles 1982).

Flow processes, variously described as debris flows, mudflows, skin flows, slurrys and other terms, exhibit various internal mechanisms and forms that, in general, result in movement without sliding through the shearing or internal deformation of sediment and water mixtures under the force of gravity. McRoberts (1978) provided a detailed discussion of slope failures in thawing permafrost slopes, including examples from alluvial valleys, as well as various methods for analyzing slope stability.

Sliding mechanisms can result in rapid bankline and bluffline recessions (10-100 m per event) over short periods. In contrast, gravitational flows are particularly important in removing thawed bluff sediments and maintaining the angle of slope and the exposure of frozen ground to the air and sun. They transport thawed bluff sediments to the slope's base, where waves and currents may remove them from the bank. Rates of bankline recession can be high; McDonald and Lewis (1973), for example, reported rates greater than 10 m per year attributable to slope failure.

At locations where currents and waves are relatively weak and cannot remove the failed material, slope angles gradually lower. Ritchie and Walker (1974), for example, recognized that coarse, cohesionless sands and gravels in bluffs thaw and fall or roll to the base where they are deposited as talus with a surface slope near the material's angle of repose. Depending upon exposure to wave and current attack, Miles (1977) concluded that the upper parts of such bluffs continue to degrade by thermal and mechanical subaerial processes, but that the toe remains relatively stable and the talus cover inhibits further bluff failure. At such locations, bankline recession ceases, although bluffline recession does not.

Other types of bluff failures were recognized by Eardley (1938), who found differences in failure modes depending on bluff composition. Frozen sand of alluvial sequences along the Yukon River was not characterized by niching, but rather by a surface that gradually sloped toward the river. Bluff sand failed only after it thawed to a depth of about 1 m, after which it broke loose as a sheet and slid along a planar surface into the river. Ice-rich loam (apparently organic-rich silt) often thawed and flowed from the bluff face to be deposited in fans at its base. Niching and failure along arcuate planes were also observed in bluffs composed of this material.

The preferential melting of ice wedges develops gullies within otherwise still-frozen bluff sediments (e.g., Lewis and Forbes 1974) (Fig. 5). When ground ice melts, it disrupts the vegetation cover, thus disturbing the thermal regime of sediments landward of the bankline. Gully sidewall materials that contain ice will then undergo thaw subsidence and consolidation. They may be modified by slumping, flow or other slope processes, as well as thermal and mechanical erosion by meltwater. Gullies widen laterally, thus expanding the thermal and physical disturbance into adjacent permafrost. This situation is analogous to the effects of human disturbances on ice-rich terrain (Mackay 1970; French 1974, 1975; Lawson and Brown 1979; Lawson 1982). Figure 6 is an example of the complex interrelationships of processes, vegetation, materials and ground ice that can result in physical modifications, and the subsequent reestablishment of physical and thermal stability following a disturbance.

Thus in terms of bluffline recession, it is important to note that erosional processes acting on the bank can trigger bluff erosion by thermal and mechanical processes, which in turn can disrupt the thermal regime of materials that are actually removed from the immediate river environment. Therefore, erosion rates and

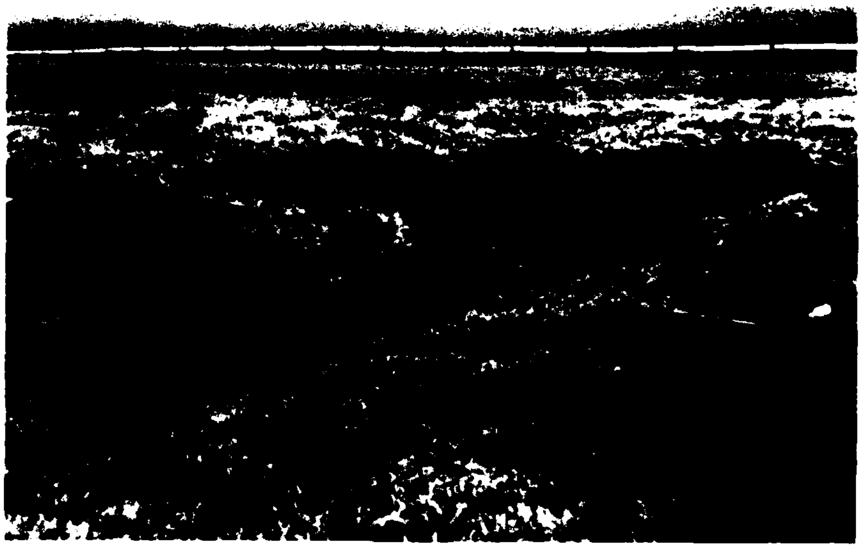


Figure 5. Gully development by thermal and hydraulic erosion above melting ice wedges, northern Alaska.

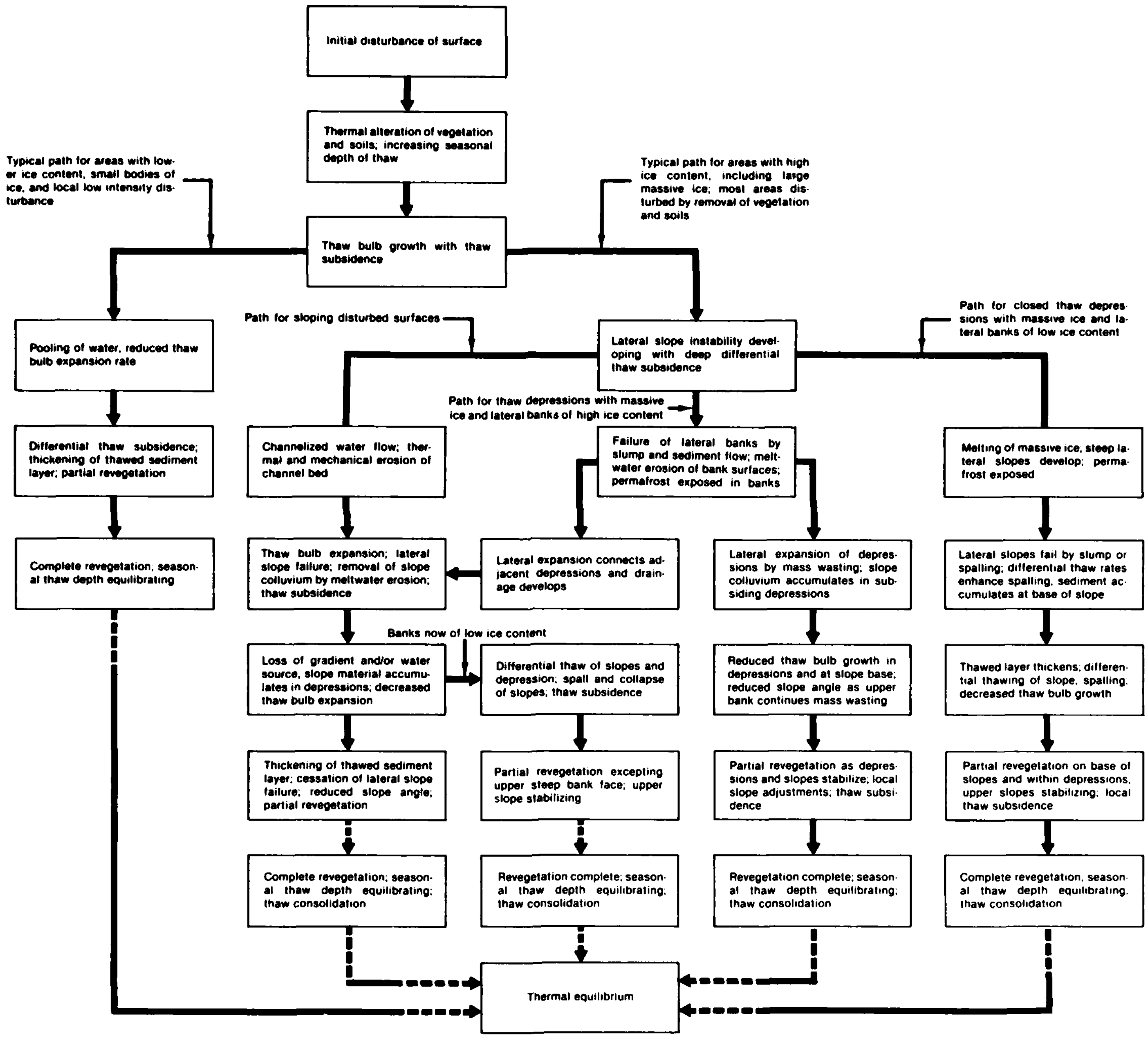


Figure 6. Schematic process-response flow chart illustrating common sequences of processes modifying perennially frozen ground at East Oumalik, northern Alaska (from Lawson 1982).

distances of bluffline and bankline recession may appear larger than those that could normally be ascribed to purely mechanical erosion by fluvial processes. My own observations (unpublished) and those of Mackay (1963, 1966), Lewellen (1972), French and Egginton (1973), McRoberts and Morgenstern (1973, 1974a), Outhet (1974a), Miles (1977) and Harper (1978) indicate the importance of streams in modifying the thermal regime of streambanks and inducing accelerated physical disruption to adjacent perennially frozen ground. Parameters affecting the thermal and physical stability of permafrost are clearly important in determining the extent of shore modifications that will take place.

Lewkowicz et al. (1978) and Claridge and Mirza (1981) discussed certain thermal and mechanical aspects of surficial erosional processes such as overland flow, near-surface groundwater flow and rainfall in modifying slopes in permafrost. In general, permafrost encourages downslope soil movement by preventing free drainage of water through the soil and by maintaining saturation of sediments into the period of autumn freezeup (Benedict 1976).

Miles (1977) cited the possible importance of nivation in eroding sediments beneath snow accumulated in bluff hollows, while Lewellen (1972) and Church and Miles (1982) have suggested that snowbanks are important because they protect streambanks from attack during spring breakup.

FACTORS AFFECTING PERMAFROST ERODIBILITY

Factors critical to an understanding of why certain perennially frozen banks or bluffs erode and recede more extensively or rapidly than others are known only in a qualitative sense from short-term observations. Primary factors identified by various authors and their apparent effects follow. Other parameters may be of importance but have not to date been addressed in the literature. For example, thermal properties of frozen bank and bluff sediments have not been analyzed in relation to water temperatures and measured thaw rates.

Exposure to currents and wind waves

Nearly all authors cited earlier consider the orientation of the bank or bluff face with respect to impinging currents or prevailing wind direction and waves as critical to determining the locations of the most active bank erosion and bluff undercutting. Thermoerosional niches can show significant variations in their growth rate and their dimensions between adjacent reaches or even opposite sides of the same reach. Some of this variability has been identified as resulting from differences in exposure to wind and waves. Similarly, exposure determines whether erosional products from bluffs are removed, thus affecting overall bank and bluff stability and morphology (e.g., Miles 1977). The importance of individual storms in producing rapid change in lake and coastal shorelines (e.g., Harper et al. 1978) suggests that storms may also be important in the wider reaches of northern rivers as well.

Texture and stratigraphy

As under unfrozen conditions, the grain size of bank sediments affects their resistance to erosion by currents and waves, with thawed cohesive material most resistant. The rate of thaw of cohesive bank material is apparently less than in noncohesive material and this affects thermoerosional niching (Scott 1978). Frozen, ice-bonded cohesive materials tend to be characterized by thermoerosional niches, whereas niches are smaller and less frequent in cohesionless sands and gravels (e.g., Eardley 1938, Williams 1952, Miles 1977). Mixtures of fine and coarse material are varied in their response. Stratified banks or bluffs of fine layers and coarse layers may lead to composite forms and failure modes in accordance with each layer's stability and ice content (Miles 1977). Frozen peat zones resist removal by both bank and bluff zone processes (Ritchie and Walker 1974).

Ice content, distribution and type

Ice directly affects bluff and bank stability as well as sediment erodibility by currents, waves and subaerial processes. Thawing of ice-rich bank material reduces its strength and thus its resistance to erosion by moving water. When ice volume exceeds pore volume, thaw subsidence in direct proportion to the quantity of ice in bed, bank and bluff sediments takes place, effectively lowering the materials in relation to the water surface.

In general, authors have concluded that materials with higher ice volumes are more susceptible to erosion than those with lower ice contents, which typically are coarser sediments (e.g., Outhet 1974a, b; Miles 1977). Bluffs of high ice content without vegetation had continuously retreating faces because of the downslope flow of sediment after thawing.

Massive bodies of ice act as planes of weakness along which there may be failure (MacCarthy 1953, Walker and McCloy 1969). Upon melting, they also cause collapse of overlying sediments and increase the exposure of permafrost to air and sun (e.g., Outhet 1974a, b; Miles 1977). Additional erosional mechanisms are thereby started that are not associated with lower-ice-content materials, and thus such ice-rich slopes with massive ice are linked to some of the highest rates of lateral recession (e.g., Mackay 1963). Thermokarst areas occur adjacent to active cut banks in ice-rich sediments containing wedges and other large ice bodies (e.g., Ritchie and Walker 1974).

Slope aspect

Ritchie and Walker (1974) emphasized that southwest-facing slopes most often exhibited active erosion in the Colville River delta, apparently reflecting the effects of the duration and intensity of exposure to solar radiation.

Coriolis force

In northern areas, the deflection of currents to the right by the Coriolis force has apparently emphasized erosion of right-hand banks in the Colville River delta area (Walker 1969).

Timing and depth of thaw

Nearly all authors agree that being frozen increases the strength of sediments, particularly those that are cohesionless when thawed (Cooper and Hollingshead 1973). Greater amounts of bluff undercutting can thus take place than can when sediments are unfrozen (e.g., Scott 1978). These statements assume, however, that the materials are ice-bonded; those lacking in water, and thus excess ice, would be unbonded and friable. They would exhibit properties similar to those of the same unfrozen material.

The timing of thaw relative to maximum water stage, discharge and current velocity is therefore critical to the immediate control permafrost exerts on bank erosion in arctic streams (Outhet 1974b, Scott 1978). Scott (1978) contends that if during breakup the bed and bank materials remain frozen, there will be little erosion. If thawing proceeds faster than erosion, there should be no direct effect on erodibility (Scott 1978). This concept neglects the fact that thawing and melting of ground ice can also affect the strength of the thawed sediments. Cooper and Hollingshead (1973), in contrast, emphasized that thawing produced an unstable and highly erodible layer, which apparently results in a relatively constant erosion rate from year to year (Gill 1972). Maximum depths of thaw in late summer coupled with summer storms and flooding are considered by Miles (1976) as most important to the timing of erosion and recession.

Water level and temperature

Water temperature as well as ground surface temperature clearly affect rates of thaw. Higher water levels keep warm water in contact with frozen sediments, thereby facilitating the heat exchange necessary for thermal erosion (Ritchie and Walker 1974). A buildup of a thawed sediment layer, however, reduces this exchange rate.

Vegetation

Vegetation is important in maintaining the thermal regime of perennially frozen sediments. Disturbance of vegetation can significantly increase the annual depth of thaw and thus decrease slope stability (McRoberts and Morgenstern 1973). A well-developed vegetative mat can reduce the effect of both subaerial and subaqueous processes (Outhet 1974b) and act as a "thermal" blanket over eroded bluff faces following erosion of the underlying sediment (Miles 1977).

Ice and snow cover

River ice and snow trapped in bank or bluff hollows protects them from the direct attack of currents, waves, wind and overland flow (e.g., Lewellen 1965, 1972; Walker 1969). Breakup in the Arctic is often preceeded by overlow of water onto the top surface of river ice, but snow along the banks protects these materials from scour during this time (Walker and McCloy 1969, Smith 1979). Banks and the lower parts of bluffs may be scoured by ice floes later in the spring; limited observations suggest, however, that they are less important in causing erosion than other processes (e.g., Outhet 1974b, Church and Miles 1982).

Groundwater

Waller (1957) concluded that streambank erosion was related to groundwater conditions in permafrost terrain at Beaver, Alaska, but other researchers have not examined this relationship.

RATES AND TIMING OF EROSION AND RECESSION

An important aspect of assessing the effect of permafrost on rates of erosion and bankline recession would be to compare measured rates from streams of varying size and location, both with and without frozen bank materials. Unfortunately, the small number of measurements, the variable but generally short periods during which rates have been measured (one to two seasons), the diversity of location and hydrologic parameters of the watersheds, and the general lack of details on measurement (or estimating) techniques make this a rather fruitless exercise. Further problems arise because bank and bluff processes are not clearly defined, and bankline versus bluffline recession rates are not always distinguished. In addition, long-term average rates of erosion have not been studied. Aerial photographs, when available, provide some documentation of long-term lateral changes in channel pattern, but there are problems inherent in this technique as well.

These limitations considered, the available data suggest that bankline-bluffline recession rates of actively eroding streambanks are highly variable and range from less than 1 m/year to over 30 m/year. Rates of 10 to 15 m/year were measured along banks affected by thermoerosional niching and block collapse during spring breakup or summer flooding, while rates of 30 m/year were measured at locations where impinging current velocities were high and block material was continually removed after failure. These measurements from Eardley (1938), Walker and Arnborg (1966), McDonald and Lewis (1973), Outhet (1974a, b), Miles (1977) and Scott (1978) were taken during field seasons lasting only several weeks and usually over a period of 1 year, but sometimes up to 3 years. Williams (1952) reported much higher recession rates of an estimated 61 m in a single summer and 10 m in 2 days along the Yukon River; in both instances, erosion was by wind waves that undercut frozen bank sediments.

Average rates of bankline-bluffline recession estimated from aerial photographs were limited to arctic regions of Canada and Alaska. Rates in the Mackenzie Delta estimated by Outhet (1974b) ranged from 1 to 11 m/year over a 20-year period, while in the Colville Delta, average rates of 1 to 3 m/year over a 3-year period were estimated by Walker (1983). Brice (1971) found an average rate of 4.6 m/year over a 20-year period at eroding sites on the Sagavanirktok River, while Scott (1978) found a maximum rate of 6.8 m/year over 5 years on the Lupine River. Both Brice and Scott found a large percentage of river reaches without detectable bankline recession.

The apparent timing of erosion and bankline recession in permafrost regions has been addressed by most authors, so it bears some mention here. Walker and Arnborg (1966) and Walker (1969) stress that most erosion and lateral recession in the Colville River takes place during spring breakup, at which time there is the most thermoerosional niching. As discharge and water level drop in summer, niching diminishes and bluff processes are most important and do not cause as rapid a retreat. Outhet (1974b) also found that the highest rates of recession correlated with the timing of spring breakup.

On the other hand, Miles (1976) concluded that breakup was relatively unimportant to erosion and bankline recession on Banks Island, N.W.T.; significant recession took place only during early summer storms. Abramov's (1957) observations suggested that bank slumping resulted in the largest recession rates and that these slumps took place in late summer.

Scott (1978) addressed this question of timing specifically, concluding that a rapid rise of the breakup flood on smaller arctic streams results in little channel bed or bank scour because materials have not yet thawed. In larger streams such as the Sagavanirktok River, breakup flooding involves higher discharge and velocities, it lasts longer, and causes significant lateral erosion and recession. He concluded that these hydraulic parameters, in relation to thawing rates of the frozen bed and bank, appear to determine the magnitude of scour and erosion.

It is important to note that no researcher has yet analyzed the effects of climate and thus thermal regime of the bed, bank and bluff in relation to stream size and hydraulic parameters, including water temperature. Climate and thermal regime are important in determining the presence or absence of a frozen bed and bank as well as the rate and timing of thaw.

OVERALL EFFECTS OF PERMAFROST

Although the intent of this review was to determine how permafrost affects the rate, style and location of erosion, and thus bankline recession rates, the question remains as to whether the overall effect of permafrost is to 1) override other processes and conditions and create a relative stability in stream channels in permafrost terrain, 2) cause unusual and rapid rates of bankline recession, or 3) have little overall effect so that the predominant erosional processes and recessional rates differ little from those of regions without permafrost. Each viewpoint has been expressed by authors cited in this report.

I do not think that there have been any studies to date that clearly indicate the effects of permafrost on streambank erosion. Certain processes and factors affecting these processes have been identified (Fig. 7), but few data exist beyond these observations. Opposing viewpoints may therefore result from the near absence of systematic observations of eroding streambanks and the total absence of quantitative analyses of erosion in relation to streambank conditions and other parameters.

My interpretation of the literature suggests that, in keeping with Scott's (1978) view, the effects of permafrost will vary, not only with hydraulic and climatic conditions in the drainage basin, but also with factors pertinent to the immediate bank zone-bluff zone environment. The thermal condition, and its change over time, is an additional and important factor affecting erosion that has not been adequately addressed by research. The numerous erosional processes commonly active in the fluvial and permafrost environment have not been analyzed in relation to thermal, physical and hydrologic conditions of streams with frozen banks. Attempting to interpret the available data further within this report would lead to unwarranted speculation.

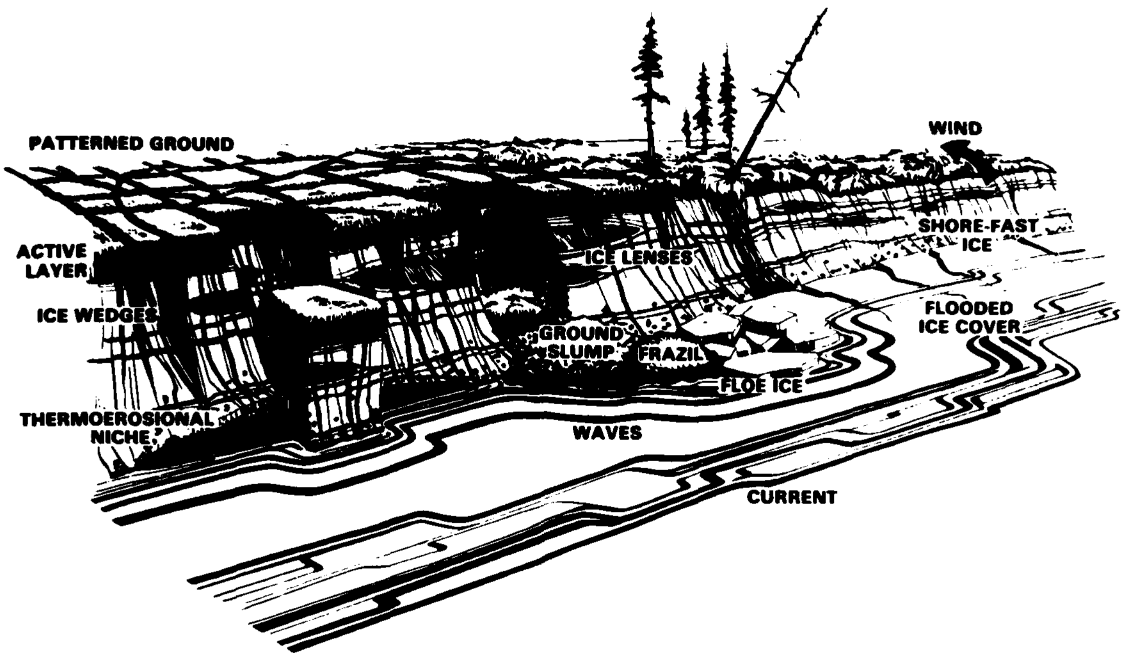


Figure 7. Idealized sketch illustrating processes and selected factors apparently important in determining erosion of streambanks in perennially frozen ground.

RECOMMENDATIONS FOR RESEARCH

There is a clear need for research on the erosion of streambanks in perennially frozen terrain. Previous studies used mostly qualitative observations of the effects of permafrost on erosion and have not succeeded in defining its importance. Locations of the dozen or so "best" analyses are in arctic regions of continuous permafrost, with far fewer observations in subarctic areas of discontinuous permafrost. Systematic observations and quantitative analyses of eroding and noneroding streambanks are needed from both regions. Other authors have previously expressed similar comments on the paucity of data from streams in permafrost terrain (e.g., Cooper and Hollingshead 1973, Newbury 1974, Scott 1978).

The following are brief recommendations for research that needs to be undertaken to understand the interaction of perennially frozen ground with fluvial processes.

First, systematic, quantitative studies of eroding and noneroding streambanks in continuous and discontinuous permafrost areas are needed that analyze:

1. the subaerial and subaqueous processes of erosion
2. the physical properties of both frozen and thawed bank and bluff zone sediments and their relationship to erosional processes
3. the thermal characteristics of bank, bluff and channel bed materials, appropriate thermal parameters of the fluvial environment, and changes in thermal stability
4. the relative importance of erosional processes at each location
5. the volumetric displacement and bankline or bluffline recession rates with time in relation to specific erosional processes and sediment properties
6. the previous research results on streambank erosion in unfrozen northern regions in comparison to the results of 1 through 5 above.

Near real-time data acquisition of climatic conditions, river parameters and other bank conditions would be desirable. Field studies should be made throughout the year, with emphasis on the spring breakup, summer season, and fall freezeup periods. Studies of this type generally need 3 to 5 years to achieve representative results.

Second, based upon results of the first recommendation at several sites, empirical equations should be developed for evaluating locations where an assessment of streambank erodibility is desired. This would assist engineers in designing suitable bank stabilization techniques. Future work should also involve the testing of these techniques.

Third, theoretical calculations and modeling of the physical and thermal conditions and processes in eroding streambanks should be undertaken, based upon field data and results defined in the first and second recommendations above.

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APPENDIX A: PROCESSES OF STREAMBANK MODIFICATIONS
(After U.S. Army Corps of Engineers 1981)

Table A1. Surficial bank mechanisms.

Mechanism	Description
Abrasion	Solid materials carried by wind or flowing water collide with and dislodge surface soil particles. Abrasion also occurs during shifting of winter ice covers.
Biological	Examples are bank surface destruction during overgrazing, animal burrowing and animal trails.
Biological (Vegetation)	Vegetation normally is conducive to surficial stability; exceptions occur during decay of root material and when tree falls or vegetation patterns concentrate streamflow or cause turbulence in overbank flows or streamflows.
Chemical	Water and acids in water affect cohesive and other types of particle-to-particle bonding; bank material is removed by dissolution.
Debris	Debris gouges bank surfaces as well as causes turbulence and flow concentration.
Flow (water)	Soil particle removal by overbank flows and streamflows is a major cause of bank surface deterioration. Quantity of flow, transport capacity, turbulence, secondary currents, and wave action contribute to the rate and location of surficial particle removal. Seepage flows remove surface particles as well as contribute to mass bank failures.
Freeze-thaw	Cyclic temperature changes cause fracture because of excessive contraction and expansion, and spalling due to successive freezing and thawing of moisture within the bank.
Gravity	A stable slope in cohesionless material corresonds to gravitational stability; for steeper slopes, surface particles may roll or bounce downslope.
Human actions	Examples of direct action on stream channels are dredging and sand or gravel mining of channel sediments. Indirect actions may include structures and vessel propeller motion that cause turbulence in the streamflow. Actions on the bank include, for example, loosening the bank surface material by farming or other mechanized operations or destruction of a protective vegetation cover by livestock overgrazing.
Ice	Ice causes abrasion and gouging. Ice jams restrict a channel and affect stream and overbank flows.

Table A1 (cont'd). Surficial bank mechanisms.

Mechanism	Description
Precipitation	Surficial destruction occurs from impact by rain or hail as well as indirectly by increased periods of high streamflows and overbank flows.
Waves	Waves from wind or stream vessel traffic cause surficial deterioration of the bank near the stream water surface.
Wet-dry	Alternate wetting and drying cause stress and chemical effects that loosen surface soil particles.
Wind	Erosion by wind is normally small compared with water flow; however, waves from wind contribute to surficial deterioration.

Table A2. Streambank failure mechanisms.

Mechanism	Description
Surficial	Stresses within a streambank may be changed by actions at the bank surface. Examples of surficial actions that affect bank stability are: a. Severe surface deterioration caused by erosional mechanisms may result in an unstable bank configuration. Erosion at the toe of the bank slope from streamflow, erosion at the water surface from waves, and erosion along the bank surface from overbank and seepage flows are three common occurrences. b. Deep tension cracks because of excessive drying of a cohesive soil or similar structural change may cause the streambank to weaken and become unstable. Slaking may occur if excessive drying is followed by submergence. c. Overburden placed along the top of a bank may cause an otherwise stable streambank configuration to become unstable.
Moisture variation	Stresses and the ability of the bank material to withstand stress without failing are both affected by moisture variation within the bank. Examples of these moisture-induced effects are: a. The slope of a cohesionless bank may be temporarily steeper than the angle of repose of the bank material because of capillary or other nonpermanent stabilizing

Table A2 (cont'd). Streambank failure mechanisms.

Mechanism	Description
	effects; when the nonpermanent effect is removed (usually by submergence and saturation of the bank material), the bank becomes unstable.
	b. During piping, cohesionless material is eroded from a location on the bank surface by seepage flow; a cavity develops and extends rapidly into the bank along a dominant seepage path.
	c. Liquefaction relates to fine-grained and loosely structured materials subject to a rapid increase in pore pressure (such as occurs during rapid drawdown or earthquake loading) and results in a large segment of bank material flowing downslope as a fluid-like mixture.
	d. During periods of high water table and low stream levels, an added hydraulic loading is placed on the bank structure; this added load may directly cause failure unless relieved by seepage.
	e. Swelling and shrinking during wetting and drying, respectively, affect the stability of clay soils. Substantial hydraulic pressures may result from water flowing freely into deep tension cracks and into openings between different bank materials.
	f. The shear strength of clay soils is highly dependent on pore pressure (slow versus quick shear) and degree of saturation.
Miscellaneous	Because of the heterogeneous or stratified character of most streambanks, combinations of failure mechanisms are common; examples are:
	a. Artesian or gravity flow within a cohesionless or porous layer that erodes sediment particles by piping can result in shear failures of layers higher in the bank.
	b. A thin clay layer that weakens and compresses during saturated bank conditions can also cause shear failures in the upper bank.
	c. High hydrostatic and seepage pressures along interfaces between bank materials can decrease resistance to sliding and result in a massive bank failure.
	d. Undercutting of composite banks by hydraulic erosion can lead to block failure of overlying cohesive sediments.

Table A3. Sediment transport mechanisms.

Mechanism	Description
Gravity	Gravity is an intermediate means for transport because either materials are removed from the site by other mechanisms or transport ceases because of accumulation.
Human action	Direct transport, such as occurs during local dredging or during mining for sand or gravel, is a site-specific event. Indirect actions are those that either enhance or inhibit natural transport and may either be site-specific or, whenever the action significantly affects streamflow transport, influence erosion at numerous sites along the stream.
Water flow	Transport by flowing water (hydraulic transport) is the most effective natural transport mechanism for streambank erosion. Hydraulic transport is categorized as stream, overbank, and seepage transport. a. Transport by streamflow is enhanced by high flow rates, high velocities and low sediment concentrations. Whenever the transport capacity is exceeded, the excess material is deposited and aggradation occurs; conversely, whenever transport is below capacity, material tends to be eroded from the streambed and banks and degradation occurs. Streamflow is determined by drainage basin, rather than local, hydrologic events. b. Overbank transport, which is a major factor in sheet and gully erosion, is hydraulically similar to stream transport. However, local rather than basin-wide hydrologic events are of dominant concern in overbank transport. c. Seepage results from groundwater flow; higher flows occur in more porous material and are commonly enhanced by local precipitation and low stream stages. Piping is an example of sediment transport by seepage flows.
Wind	Exposed fine-grained cohesionless sediments are transported by wind.

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